МЕТОДИ ТА ЗАСОБИ ДОСЛІДЖЕНЬ СВІТОВОГО ОКЕАНУ

УДК 556; 574.653

Black Sea ARGO

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Abstract. The article provides an overview of the Black Sea Argo program as the first whole basin scale in situ observing system that provides near real time data of essential ocean variables in the Black Sea, which meet FAIR principles (findability, accessibility, interoperability and reusability) and which are used widely for scientific research, monitoring, modelling and forecasting.

Key words: Argo floats, Black Sea, monitoring, modelling, forecasting.

Introduction. Black Sea is virtually isolated from the rest of the European Seas except a limited exchange through the Bosporus and Dardanelles straits system. It has highly dynamic and complex eddy-driven circulation system and is the largest anoxic water body in the world. Black Sea receives drainage from almost one-third of the continental Europe which includes 17 countries, 13 capitals and 160 million people and is one of the most eutrophicated basins among the European seas. The sustainable development of Black Sea region, the management of its resources is serious concern for the countries bordering the Black Sea. A crucial element of the restoration and rehabilitation initiatives is to implement a continuous monitoring and observing system contributed by all member states in the region. The Black Sea observing system is urgently required for sustained operational oceanographic studies, the model assessment and validation as well as better accuracy and reliability of forecasts. Furthermore, noting that the Black Sea ecosystem is characterized by a series of simultaneous highly transient and perturbed states during the last three decades, assessing likely future trajectory of the ecological state requires understanding and modelling long-term trends of ecological characteristics with the support of systematic observations. This is especially valid for the deep parts of the sea, where the data acquisition is difficult and expensive. A well-developed ARGO program could to overcome these limitations.

Argo is an international program that collects information from inside the ocean using a fleet of robotic instruments (called Argo floats) that drift with the ocean currents and move up and down between the surface and a mid-water level [1]. At present Argo is collecting more than 12,000 data profiles each month (400 a day). This greatly exceeds the amount of data that can be collected from below the ocean surface by any other method. Argo plans to continue its data collection for as long as those data remain a vital tool for a wide range of ocean applications of which understanding and predicting climate change is but one.

There is no central funding for Argo. The Argo array is made up of 30 different countries' contributions that range from a single float up to 50% of the global array [12] – Fig.1. Each of the 30 countries that established their Argo program obtains national funding to for float purchase,

deployment and data delivery. Several other countries have assisted greatly with float deployments using everything from small research vessels to huge container ships. The Argo Program is managed by teams of scientists and data experts who ensure that the program is run as efficiently and effectively as possible and that standards are maintained at the highest possible level. Argo is part of the Global Ocean and Global Climate Observing Systems.

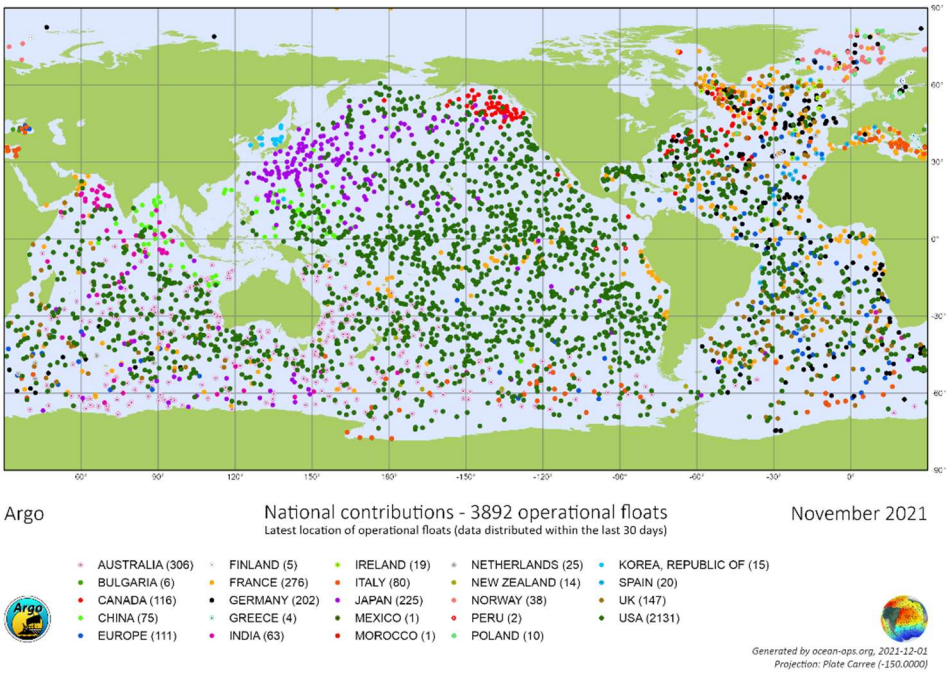

Fig. 1. National contribution to ARGO program – operational floats November 2021

Started in January 2008 as a European project involving 25 organizations from 12 countries, Euro-Argo gained the status of a European Research Infrastructure Consortium (ERIC) in May 2014 [4]. In 2018 Bulgaria was the first Black Sea country joined Euro-Argo ERIC. The common aim of Euro-Argo is to provide an optimized and sustained European contribution to Argo by deploying 250 floats per year.

ARGO data management. A fundamental rule for Argo is that all data are freely and openly available. Every effort is made to deliver the quality-controlled data in near real time. The quality control procedures are the highest and most stringent for the delayed-mode data stream which is designed to deliver data for climate studies.

The international Argo Data System is based on two Global Data Assembly Centers [3, 11], a series of 11 national Data Assembly Centers (DACs) and several Argo Regional Centers. The float measurements are sent to regional data centers where they are given rigorous quality checks and then passed to two global data centers from where they can be accessed by anyone wishing to use them. GDACs (Global Data Centers), located at Coriolis/France and FNMOC/USA, are in charge of collecting the processed Argo data from the 11 DACs and to provide users with access to the best version of an Argo profile. Data are available, in a standard NetCDF and ASCII formats both on FTP and WWW. The two GDACs synchronize their database every day.

ARCs (Argo Regional Centers) provide wide expertise on specific geographical ocean regions in order to provide the most comprehensive data sets (including non-Argo data) of the highest quality. Mediterranean & Black Sea Argo Centre [10] is an ARC for the Black Sea.

ARGO data can also be found on the websites Ocean-OPS [12] and Euro-Argo [5].

ARGO in the Black Sea. The first ARGO float was deployed in the Black Sea in 2002 [14]. Totally 48 ARGO floats are deployed from 2002 to 2021 – Fig. 2. Thirteen of them are still active – Fig. 3.

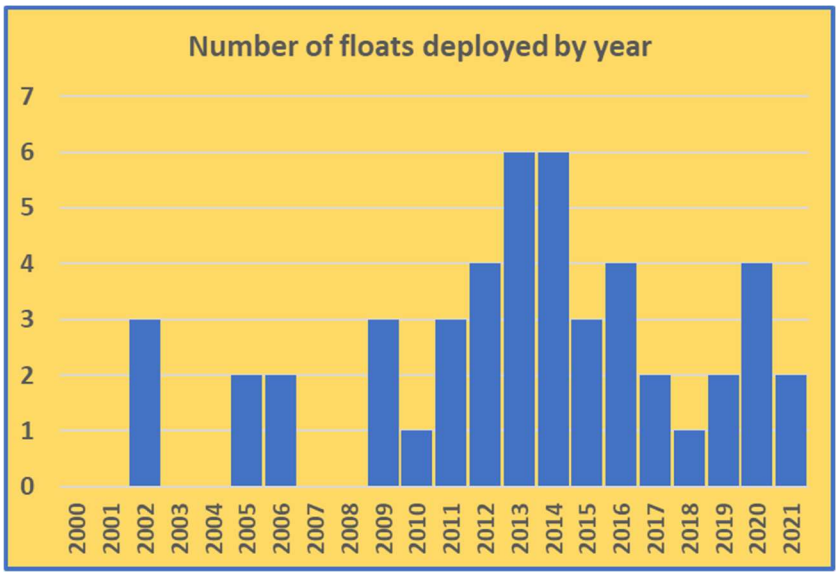

Fig. 2. Number of ARGO floats deployed in the Black Sea 2002-2021

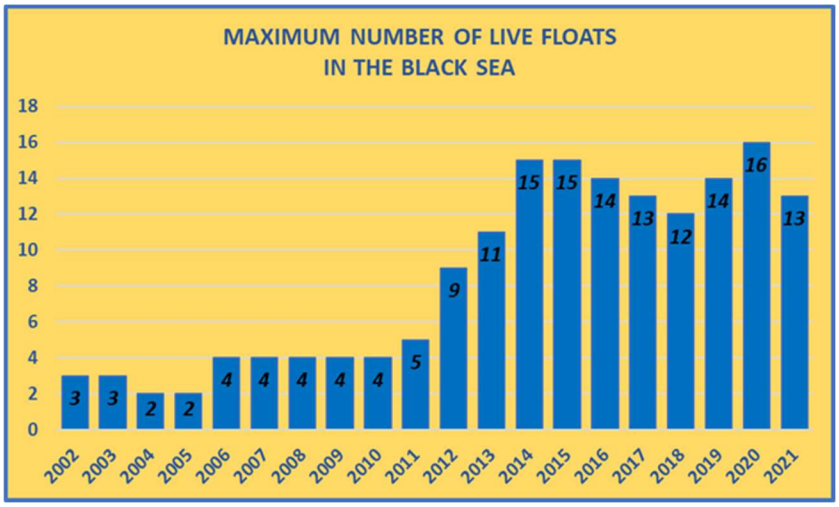

Fig. 3. Maximum number of active ARGO floats in the Black Sea during years 2002-2021

The Black Sea Argo story began in September 2002 when three profiling floats, assembled by the School of Oceanography–University of Washington, were deployed in the southwestern Black Sea, approximately 180 km offshore of the Bosporus Strait [8]. The US-Turkish-Ukrainian collaboration in the frame of the project "Observing the Black Sea with Profiling Floats" funded by the NICOP program led to deployment in total 7 APEX floats in the Black Sea within the period

2002-2006. The primary aims of this project were to improve the capability for near-real-time temperature and salinity measurements within the entire water column of the Black Sea, and to promote a better understanding of the intermediate and deep circulation and seasonal and inter-annual dynamics of water mass characteristics. The last profile form US-TR-UA floats was obtained in December 2009. Their estimated average life time was about 3 years, but the quality of the data was not always high [17].

This pioneer initiative was followed by several scientific oceanographic programs in the Black Sea aiming to contribute towards development of the regional research infrastructure in support of Euro and Global Argo networks. In June 2009 Helmholtz-Zentrum Geesthacht and Max-Planck-Institut fuer Marine Mikrobiologie institutes co-jointly deployed in the Black Sea two NEMO floats with oxygen sensors during a research cruise with R/V Maria Merian in the frame of HYPOX Project [22]. The main scientific goal of the project was to monitor oxygen depletion and associated process in the semi-encloses basins with permanent anoxia. Both floats ceased operating after 120 and 187 cycles, respectively.

Few months later accelerated deployment started with Euro Argo Black Sea Workshop, Varna, Bulgaria, 7-8 December 2009 where the representatives of all Black Sea countries took part. The workshop was combined with training of ARGO float deployment onboard of RV "Akademik". In December 2009 and April 2010, within EURO-ARGO program, French Institute IFREMER deployed two PROVOR floats in the Western Black Sea [17]. One of the floats was additionally equipped with oxygen sensors, but stopped operating after only 24 cycles.

In 2011 a BulArgo program was initiated in Bulgaria. The project was funded by Bulgarian National Science Fund of the Bulgarian Ministry of Education, Youth and Science. The main objectives of the BulArgo project were: 1) to develop national research infrastructure as a Bulgarian component of the Euro-Argo network; 2) to increase sources of the Black Sea *in situ* data and to improve quality of local oceanographic products and forecasts and 3) to promote international collaboration towards establishment of a Black Sea Argo program [15, 16]. Four BulArgo floats were deployed in the western open Black Sea in March 2011 and August 2013. Apart from the standard CTD measurements, one of the floats was equipped with an oxygen sensor. All floats use ARGOS telemetry system, and were programmed to a 5-days cycle, a parking-depth at 750 m and a profile depth at 1500 m (Fig. 4).

In August 2013 and May 2014, in a frame of DEKOSIM (Marine Ecosystems and Climate Studies Center) project, scientists from Institute for Marine Sciences (IMS), Erdemly, Turkey deployed four PROVOR floats with DO sensors in the southern Black Sea, as two of them have two-ways IRIDIM communication.

Since June 2012 in a frame of a collaborative effort with Italy, Institute of oceanology, Bulgarian Academy of Sciences (IO-BAS) has deployed 12 ARGO floats, including Argo core (T/S) and BGC (BioGeoChemical) floats, in the western Black Sea as contribution of the MedARGO program.

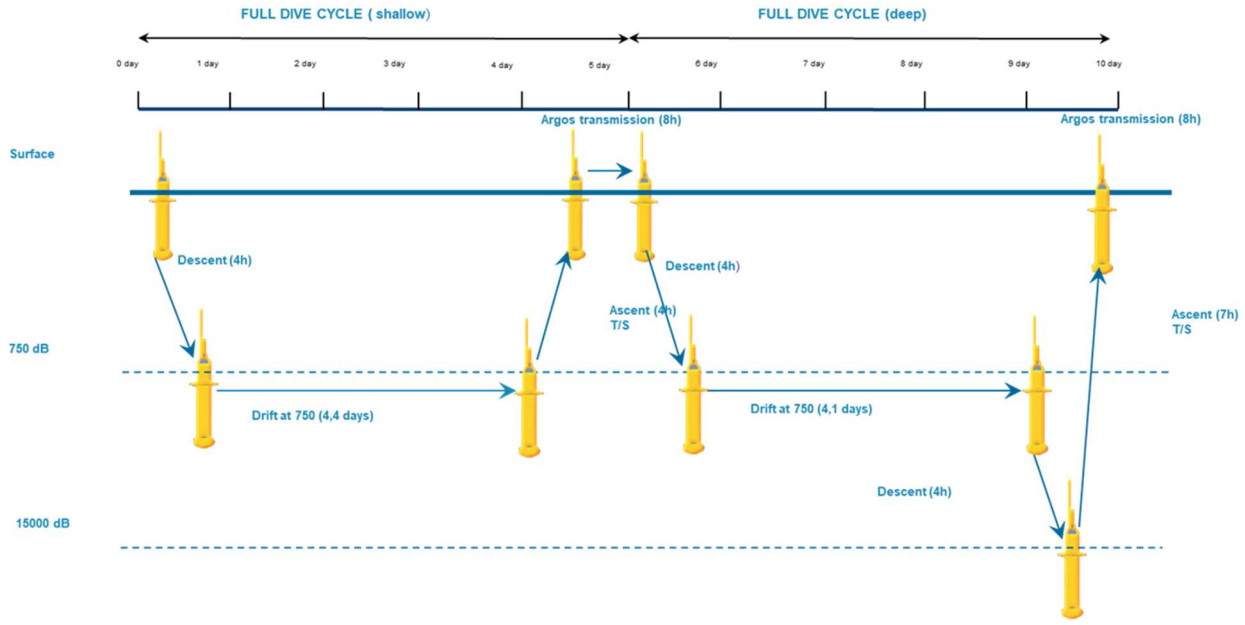

Fig. 4. Typical Black Sea float cycle

In December 2013, two BGC PROVOR CST4 floats were deployed in the western Black Sea by IO-BAS in the frame of E-AIMS, EC 7FP project. In addition to the standard CTD, each float mounted the following set of biogeochemical sensors: 1) Aanderaa oxygen optode 4330; 2) Satlantic Rem-A sensor including a WETLabs ECO-Triplet (with three channels to measure chlorophyll-a fluorescence, and optical backscattering at 532 and 700 nm) and a Satlantic OCR540 (with four channels measuring downward irradiance at 380, 412, 490 nm and a channel for photosynthetically available radiation, PAR).

The BGC floats were programmed to collect data over the top 1000 m. They transmit data via two-ways IRIDIUM/RADICUS satellite communication that allows changes of the floats mission parameters underway. The main objectives of the Black Sea Bio Argo experiment are: 1) to investigate the seasonal evolution of oxygen in the upper layers, including the subsurface oxygen maximum; 2) to study the seasonal and interannual dynamics of phytoplankton blooms in the deeper Black Sea and 3) to test the bio-optical sensors performance in the Black Sea. The Bio Argo data are processed by Marie Optics and Remote Sensing lab, Villefrance and distributed via Ocean autonomous observations web site (www.oao.obs-vlfr.fr).

In period 2014-2015 three PROVOR CT (2 with DO sensors and one with DO, Chl, CDOM and backscattering sensors), were delivered under PERSEUS EC 7FP project. Two of them were deployed in the Bulgarian Black Sea waters during the R/V "Akademik" monitoring cruises. The third float was launched in Romanian waters by GeoEcoMar.

In the frame of Monitoring the Oceans and Climate Change with Argo (MOCCA) project, Euro-Argo ERIC with collaboration of Bulgaria, Romanian and Turkey deployed three Argo core floats in the Black Sea.

Under the H2020 project EA-RISE the investigation of the potential of Argo profiling floats to operate in the Black Sea shelf areas and fill the monitoring gap between offshore and shallow waters

was carried out. Two floats were deployed in the North-Western and Western shelf of the Black Sea in front of Danube delta (OGS with the collaboration of Romanian institute GeoEcoMar) and Kamchia river delta (IO-BAS) [13]. Floats were controlled using specific available monitoring tools and home-made tools.

On April 5th, 2018, Bulgaria has become a regular member of Euro-ARGO ERIC and as such has the obligation to ensure deployment of at minimum of 3 Argo floats per year. The BulArgo program is a component of the project MASRI – Infrastructure for Sustainable Development of Marine Research and Participation in the European Infrastructure EuroArgo (http://masri.io-bas.bg/), a part of the National roadmap for scientific Infrastructure of Republic of Bulgaria (2020-2027). The BulArgo comprises a consortium of three scientific organizations: Institute of Oceanology (IO-BAS) in Varna, Sofia University "St. Kliment Ohridski" and National Institute of Meteorology and Hydrology in Sofia.

Six countries and EU contribute to the Black Sea ARGO – Fig. 5. Bulgaria and Turkey are the Black Sea countries contributing to Black Sea ARGO. Romania supported Black Sea ARGO deployments [2].

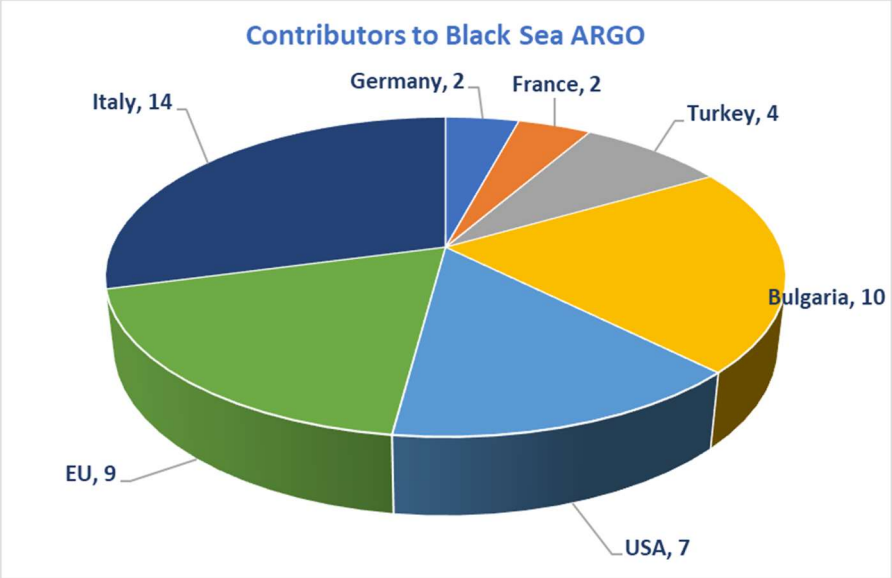

Fig. 5. Contributors to Black Sea ARGO

Black Sea is considered as marginal sea and it is important to know the life time of Argo floats in the basin. The Black Sea Argo experience shows that the average lifetime of the floats in Black Sea is not dramatically different from those in open oceans [7] and is about 38 months (Fig.6).

Value of ARGO data. ARGO data is coming in NRT, they are quality checked and freely available. The amount of ARGO profiles from the Black Sea is increasing every year while CTD profiles from research vessels are decreasing and are freely available in delay mode after a year (Fig. 7).

This make ARGO data to be used widely by large group of scientists. There are several important scientific results achieved using the free ARGO data. Here are only few examples.

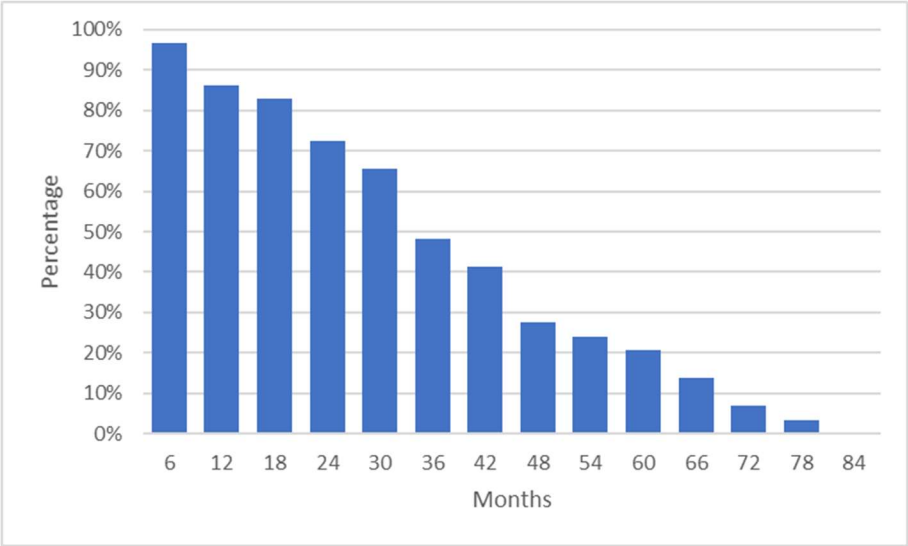

Fig. 6. Black Sea Argo floats lifetime

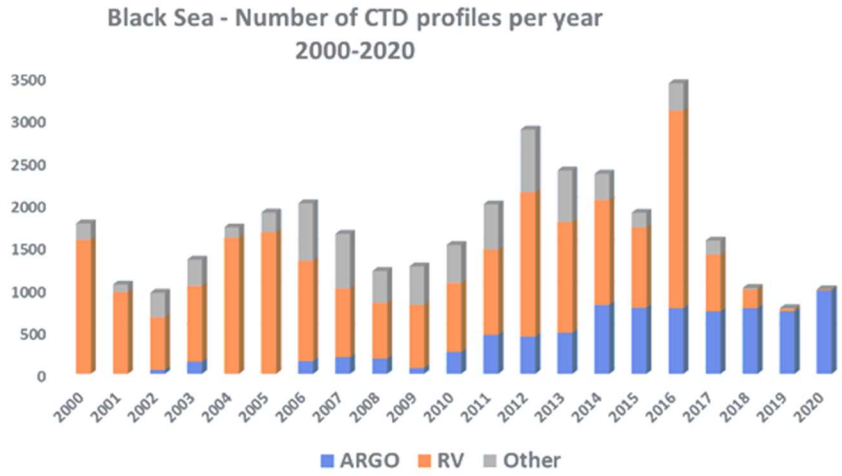

Fig. 7. Number of CTD profiles from the Black Sea per years (source SeaDataNet)

Using 33 ARGO floats and 5884 profiles it was found [20] that the temperatures in the Black Sea Cold intermediate layer (CIL) are currently substantially higher than the values known from historical data. The Argo floats registered temperatures in the core of the CIL lower than 8°C during only the first three to four years of the period of 14 years. Starting in 1991, the temperature in the core of the CIL increased by more than 1°C until now, which was mainly due to an increase over the last 14 years of 0.7°C.

CTD profiles obtained from ships (2008–2009) and 657 Argo profiles (2005–2009) are analyzed [6] and suggested that the most prominent middepth (100–600 m) Mediterranean outflow waters intrusions in the Black Sea originate from strong injections of Mediterranean water during strong cyclonic storms over the Bosporus Strait. Such intrusions propagate in the Black Sea over much larger area than was previously reported.

The reconstruction of the geostrophic currents using Argo and altimetry data [18] show the vertical extension of the main circulation features in the Mediterranean and Black Seas and define a reversal of the intermediate currents with respect to the surface in the eastern basin of the Black Sea.

Black Sea ARGO is a main source of near real time data for modeling and forecasting the Black Sea in the frame of CMEMS Black Sea Monitoring and Forecasting Center [9]. ARGO data is used also by other Black Sea modelers and forecasters.

The Chla profiles derived from five BGC floats deployed in the Black Sea for the period 2014-2019 were used to investigated the vertical structure of the phytoplankton bloom and, in particular, the process of formation and maintenance of the Deep Chlorophyll Maximum [19].

Observations collected in the Black Sea from May 2010 until December 2011 from two Argo floats with oxygen sensors were used to demonstrate the potential of the applied technique to deliver high-quality oxygen data in this oxic/anoxic environment where the oxygen concentration varies from the level of saturation to zero. It was demonstrated that mesoscale processes contributed largely to the dynamics of suboxic zone bring in anoxic waters up to about 50 m or deepening of the pycnocline down to 150-200 m [21].

Why we need Black Sea Argo. There are several important reasons to use ARGO in the Black Sea:

- Lack of real time oceanographic data;
- Scare resources for organization of regular research cruises in the Black Sea (especially in its open part);
- BS Monitoring and Forecasting Systems need in situ data for assimilation and validation;
- Reference in situ data is mandatory for regional satellite products validation and calibration;
- Assessment of global change and its regional impact required sustained observations of the marine environment;
- Marine industry needs marine products (shipping, fishery, tourism, aquaculture);
- Safety at sea needs real time data and forecasts (search and rescue, oil spills combat);

The main goal of the Black Sea Argo [14] is to provide continues whole-of-basin autonomous near real time monitoring, even though that the floats were deployed to serve different research objectives of the various international and national projects. The Black Sea ARGO specific objectives can be divided into 3 major groups, as each group has several subtasks (Fig.8).

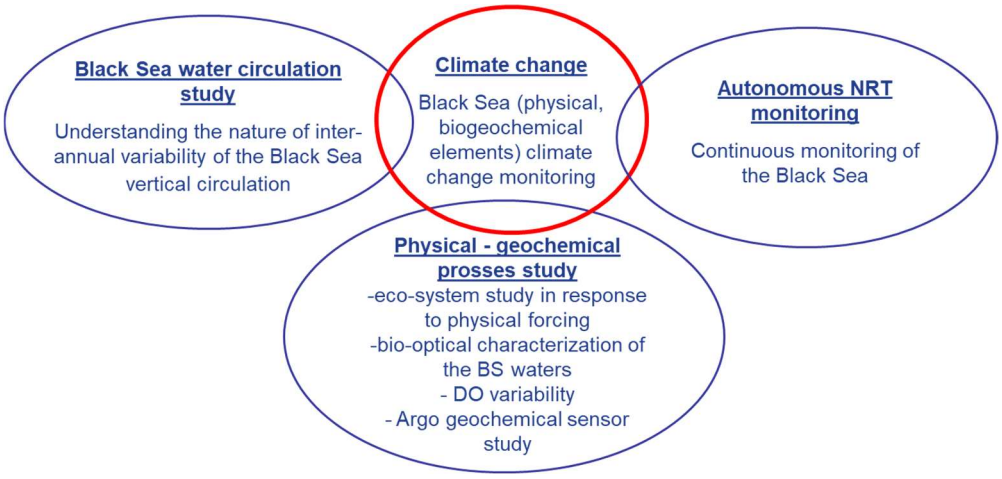

Fig. 8. Black Sea Argo goal and specific objectives

This new knowledge will provide scientific basis for developing new products for the support of the sustainable development of the blue economy in the Black Sea as well as will contribute to achieving UN Goal 14 for Sustainable Development: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

Conclusions. Black Sea Argo program is the first whole basin scale in situ observing system that provides near real time data of essential ocean variables in the Black Sea, which meet FAIR principles of findability, accessibility, interoperability, and reusability and which are used widely for scientific research, monitoring, modelling and forecasting.

Regardless of results achieved so far, for sustainable operation of Black Sea Argo extended collaborative efforts of the all Black Sea riparian countries are required for contribution to the program.

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Програма ARGO для Чорного моря

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Анотація. У статті надано огляд програми Black Sea Argo – першої системи спостережень *in situ* у масштабі всього басейну, яка надає близькі до реального часу дані про найважливіші океанські змінні у Чорному морі, що відповідають FAIR принципам (виявлення, доступність, сумісність і можливість повторного використання), і які широко використовуються для наукових досліджень, моніторингу, моделювання та прогнозування.

Ключові слова: буї Арго, Чорне море, моніторинг, моделювання, прогнозування.

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Аннотация. В статье представлен обзор программы Black Sea Argo – первой системы наблюдений *in situ* в масштабе всего бассейна, что предоставляет близкие к реальному времени данные о важнейших океанских переменных в Черном море, которые соответствуют FAIR принципам (обнаруживаемость, доступность, функциональная совместимость и возможность повторного использования), а также широко используются для научных исследований, мониторинга, моделирования и прогнозирования.

Ключевые слова: буи Арго, Черное море, мониторинг, моделирование, прогнозирование.

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